NCSP related Nuclear Data Measurements at RPI

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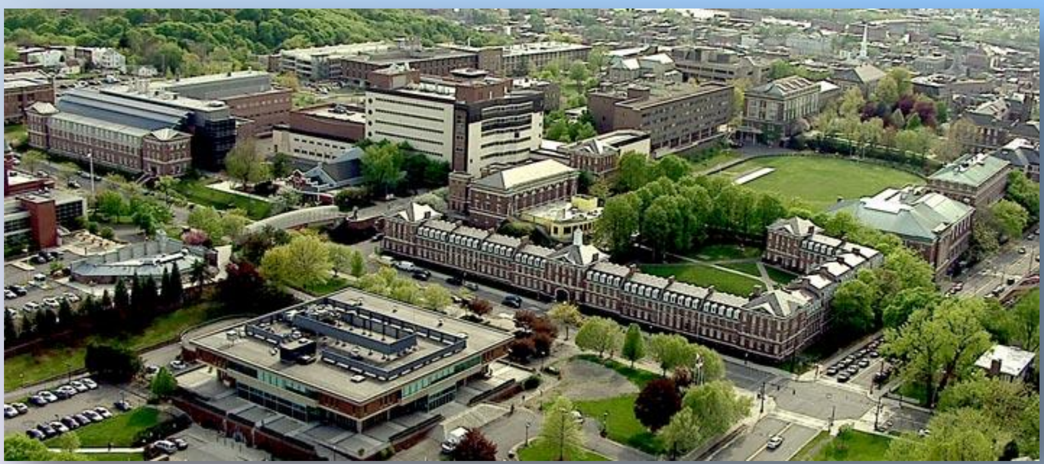

NCSP Meeting, SANDIA, March 15-16, 2016

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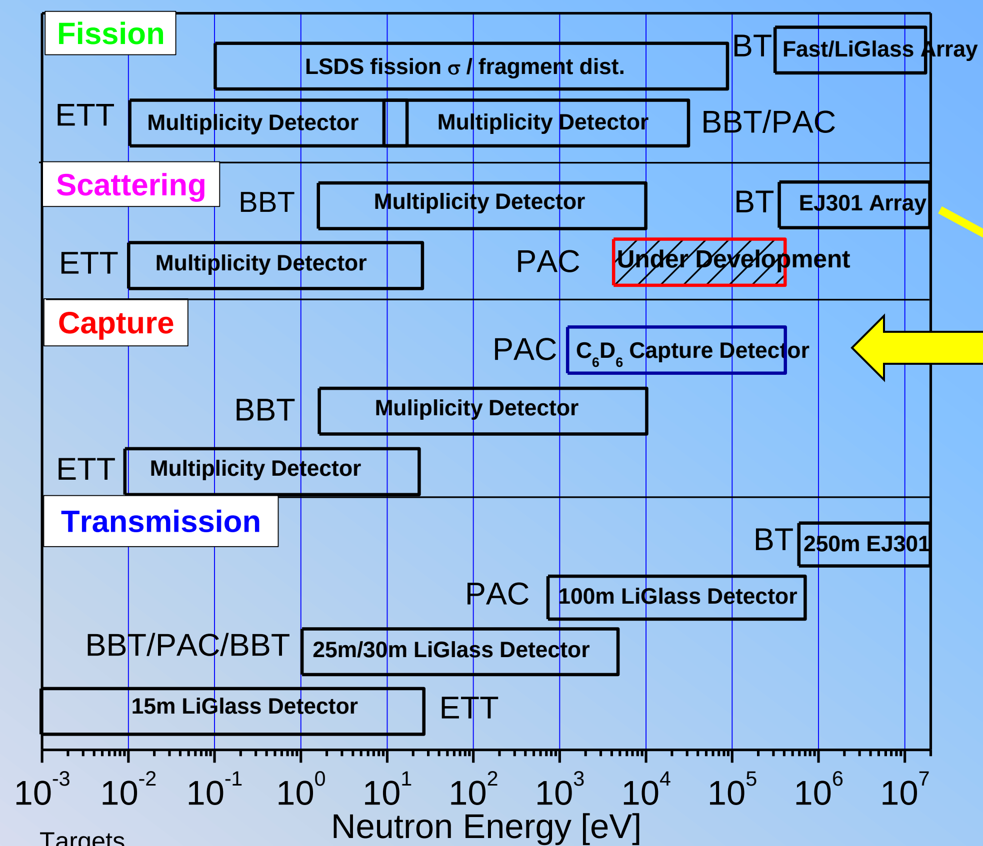
RPI ND program Overview

- **ND-1- Resonance Region Nuclear Data Measurement**
  - Development of a new mid energy capture detector
    - Performed measurements of Fe, Fe-56 and Ta,
    - Demonstrated capture measurements up to 2 MeV and in the resolved and unresolved resonance region.
  - Neutron scattering measurements for Fe (PhD thesis submitted, paper in internal review)
    - 30m flight path, 0.5 MeV to 20 MeV
    - Obtained the ratio of inelastic to 1st state to elastic scattering.
    - Obtained elastic scattering angular data to improve ORNL fit to extend the RRR to 2 MeV
    - Performed benchmarking of new IAEA evaluation
- **ND-2 Thermal Neutron Scattering Measurements**
  - Measurement of the thermal neutron scattering
    - Scattering kernel for polyethylene at room temperature was developed based on the experimental data.
    - Analysis of SiO2 measurements in progress
- **ND-3 LINAC 2020 Refurbishment and Upgrade Plan**
  - Klystron order in progress one Klystron passed factory acceptance test
  - Modulators purchase recommendation submitted by RPI to BMPC
  - Detailed accelerator design is in progress at SLAC.

Capability Development

- Developed Mid energy (1 - 500 keV) capture detector



Targets

ETT- Enhanced Thermal Traget

BBT - Bare Bounce Target

BT- Bare Target on Axis

PAC - PacMan Target

ND 1 – Cross Section Measurements – Development of capabilities in the keV region

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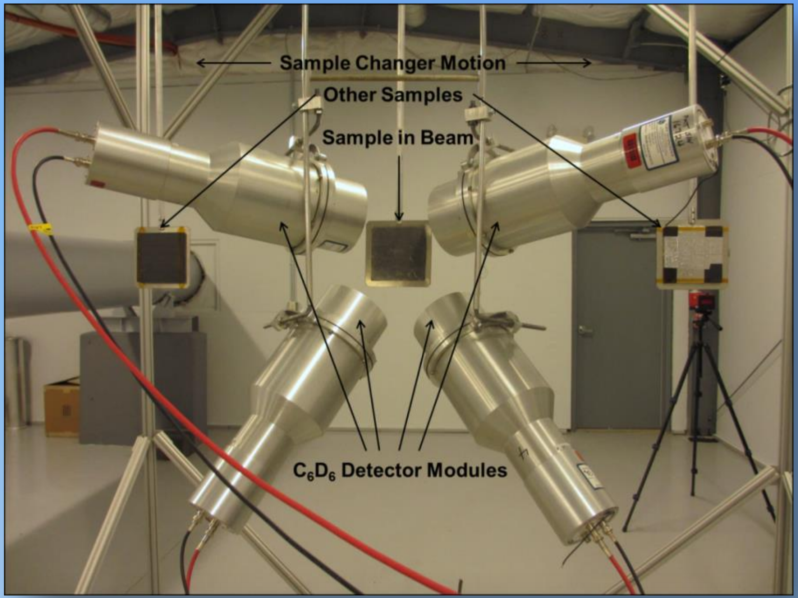
Mid-Energy Capture Detector System Overview

- 4 C_6D_6 detector modules manufactured by Eljen Technology
- **Low mass, low neutron sensitivity design**
- Located at 45m flight path in newly constructed flight station
- Measurements made from 1 eV to 1 MeV



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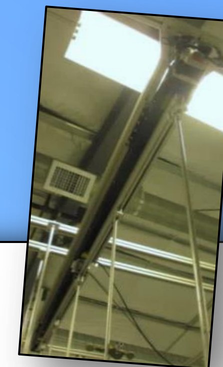
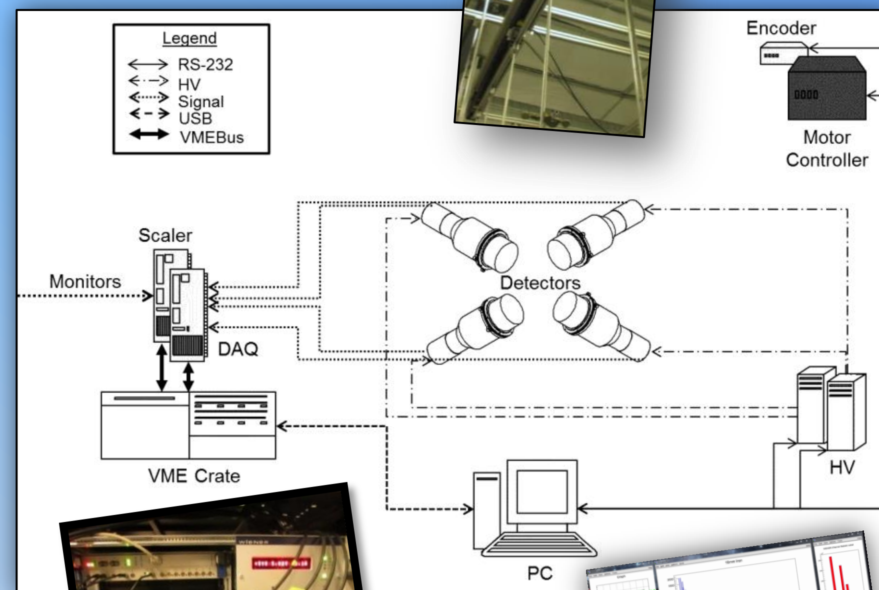
Mid-Energy Capture Detector System Overview

- **Sample Changer**
  - Velmex BiSlide linear translation table w/ stepper motor and magnetic position encoder
- **Data Acquisition**
  - 8-channel SIS3305 digitizer w/ 10-bit, 1.25GHz functionality
- **Beam Flux Monitoring**
  - 8-Channel MDGG-8 Flexible Delay/Gate Generator & Scaler
- **Detector Bias**
  - 2 Dual-channel 3kV NHQ-203M high voltage supplies
- **Software**
  - Custom C/C++ libraries for system control, data acquisition, visualization and data analysis

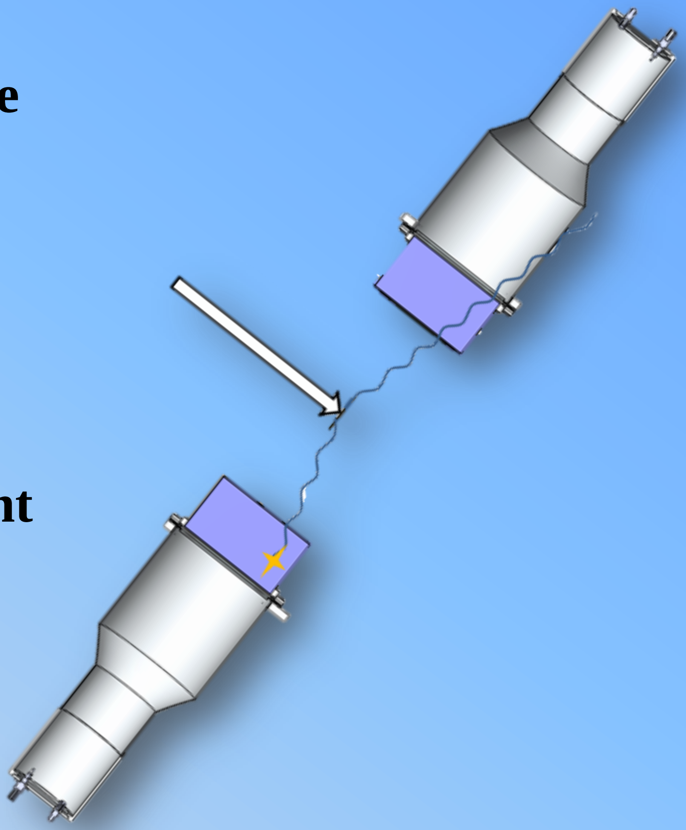




Mid-Energy Capture Detector Principle of Operation

Uses the "**Total Energy**" detection principle:

1. Detect only a **single photon per capture** cascade
2. Assert that the detection **efficiency is proportional** to the incident photon energy
3. Given 1 and 2, it can be shown that the total **efficiency to detect a capture event is proportional to the total excitation energy** of the compound nucleus, and insensitive to the cascade.



Requires a weighting function to correct for detector efficiency

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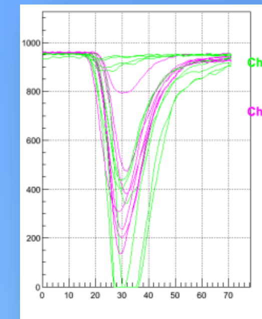
Typical Data Analysis



- For every detected event *j* in TOF channel *i:*
  - Obtain the pulse integral $I_{i,j}$
  - Use the energy calibration to obtain $E_{i,j}$
  - Sum all weighted events for the sample C^s, its background C^{sB}, the flux C^{ϕ}, and its background $C^{\phi B}$:

$$C_i^x = \sum_j^{n\text{ events}} W\left(E_{i,j}\right) \qquad \text{non weighted case:} \quad C_i^x = \sum_j^{n\text{ events}} 1$$

  - Calculate the capture Yield:

$$Y_i^s = \frac{C_i^s - C_i^{sB}\dfrac{m^s}{m^{sB}}}{\left(C_i^{\phi}\dfrac{m^s}{m^{\phi}} - C_i^{\phi B}\dfrac{m^s}{m^{\phi B}}\right)} Y_i^{B_4C} n$$

Where m^x are the beam monitor counts

Incident Neutron Flux

  - Normalize the yield (find *n*)
    - To a known black resonance, or to a transmission measurement.

Neutron Flux Shape Measurements

- Below 1 MeV can be measured using a B_4C sample enriched with ^{10}B.
- For E>1 MeV
  - We developed and tested a prototype 3mm plastic scintillator detector.
  - Several flux measurements were performed with the plastic detector and a 1.27cm thick liquid scintillator (EJ301)
  - We still need to better characterize the efficiency of the plastic detector

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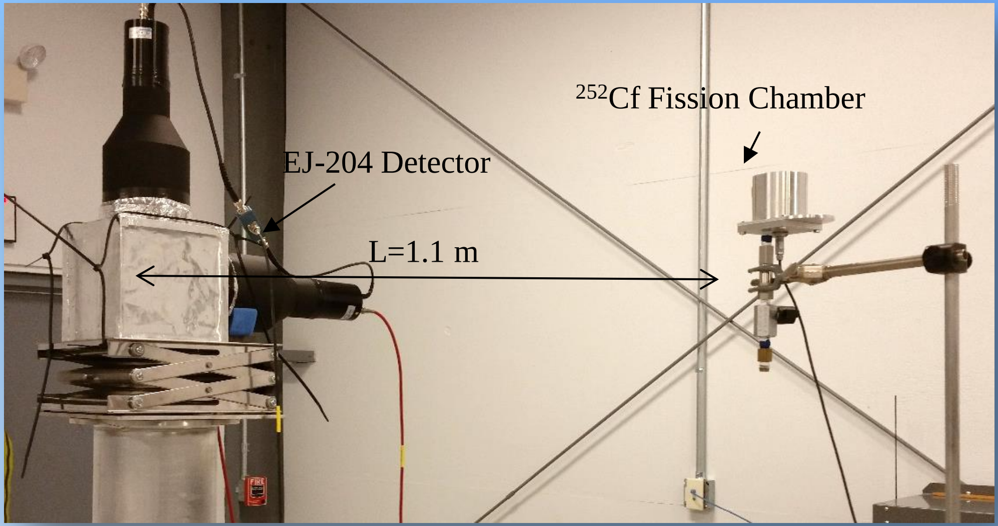
Flux Measurements for E>1 MeV

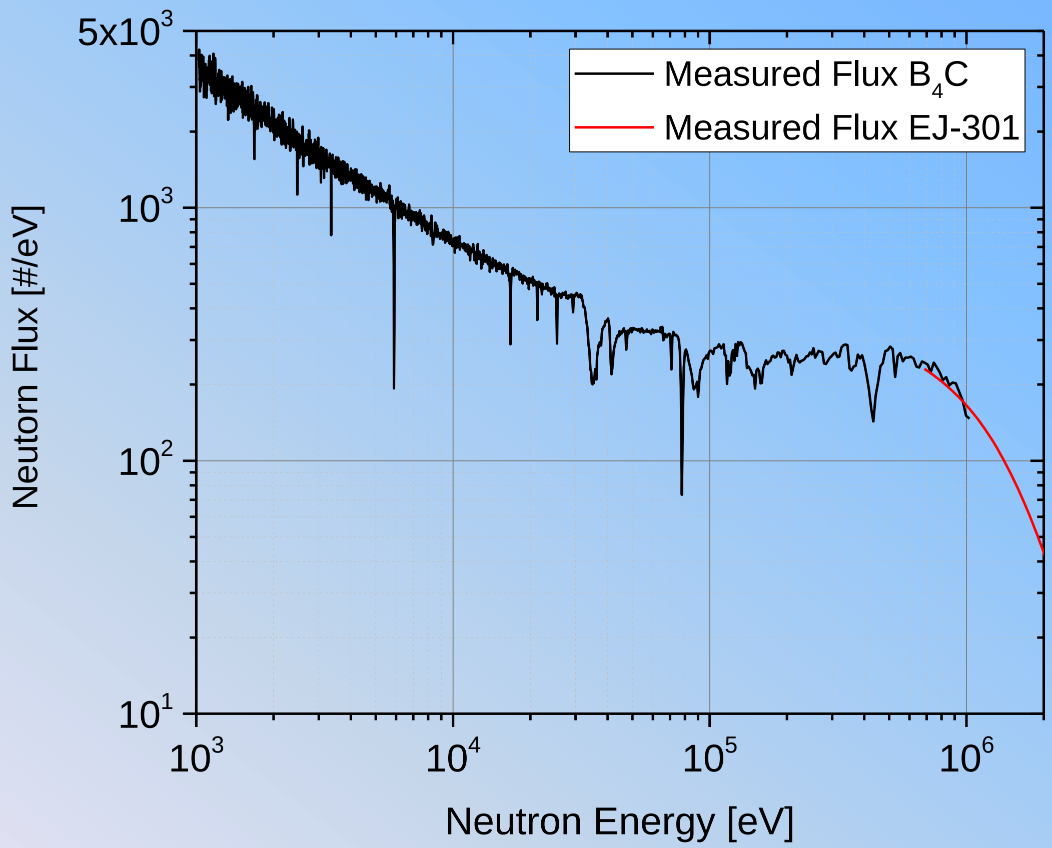
- Efficiency calculations performed with SCINFUL code

- Efficiency measurements performed with ^{252}Cf fission chamber operated in TOF mode



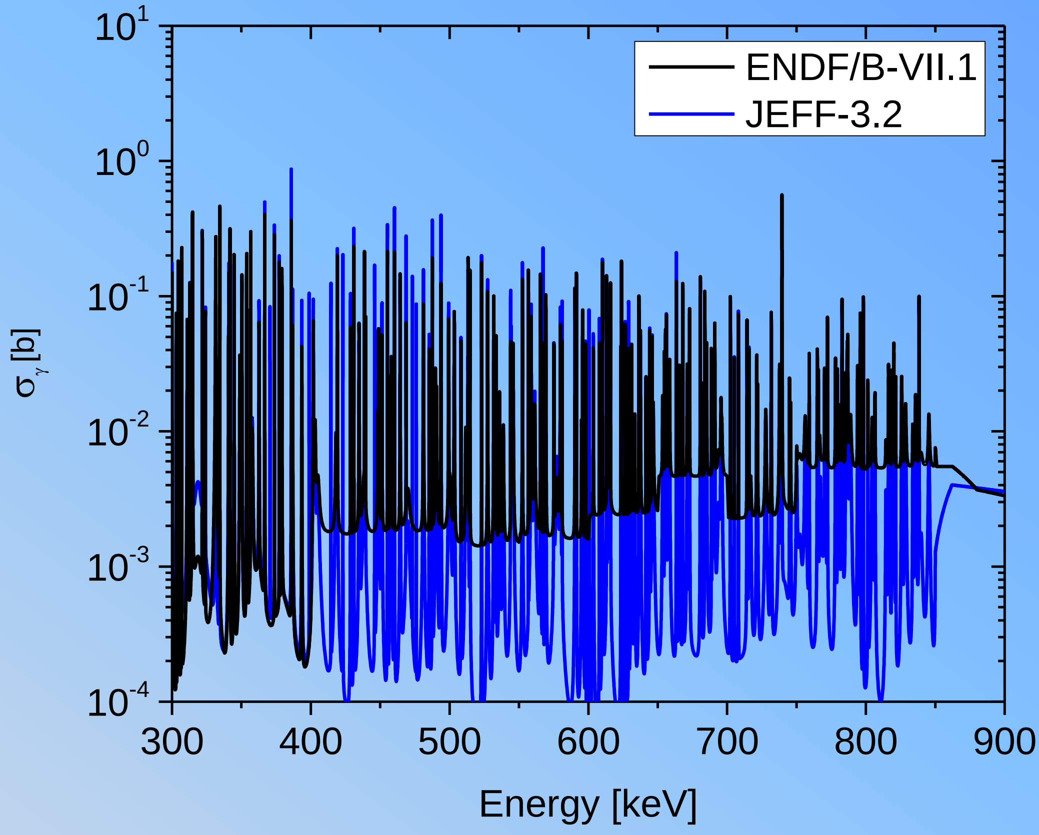
Measured Flux Shape

- Flux shape used for analysis of capture data for E>1 MeV



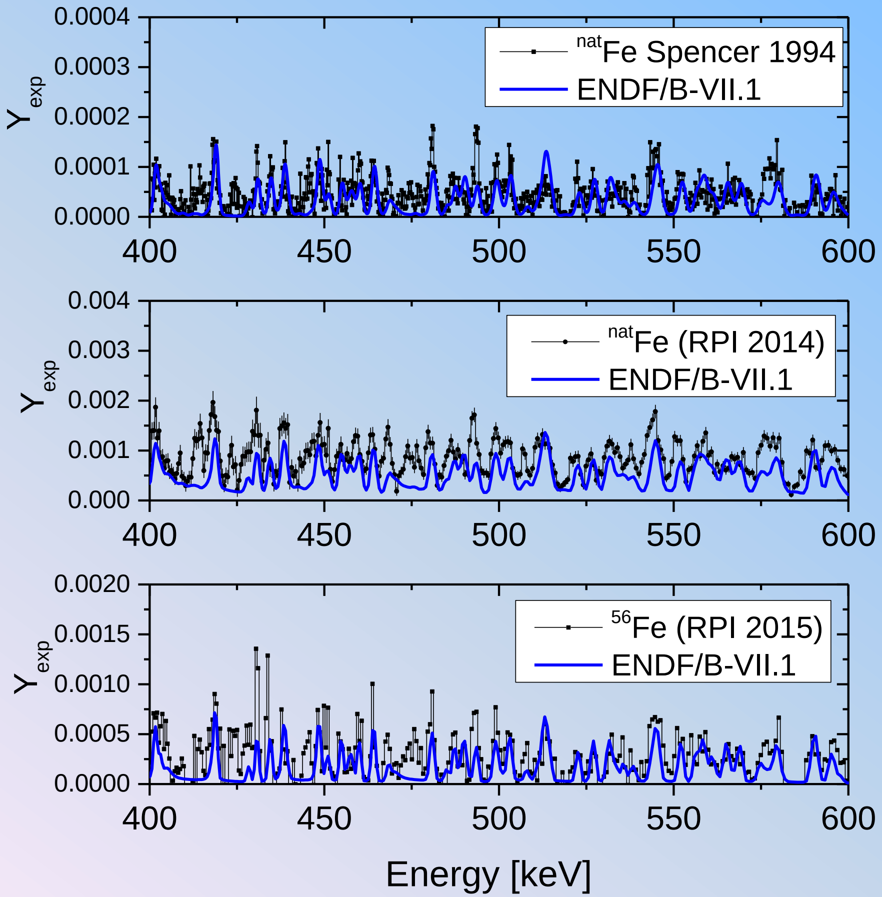
Mid-Energy Capture Experimental Results- ^{nat}Fe, ^{56}Fe

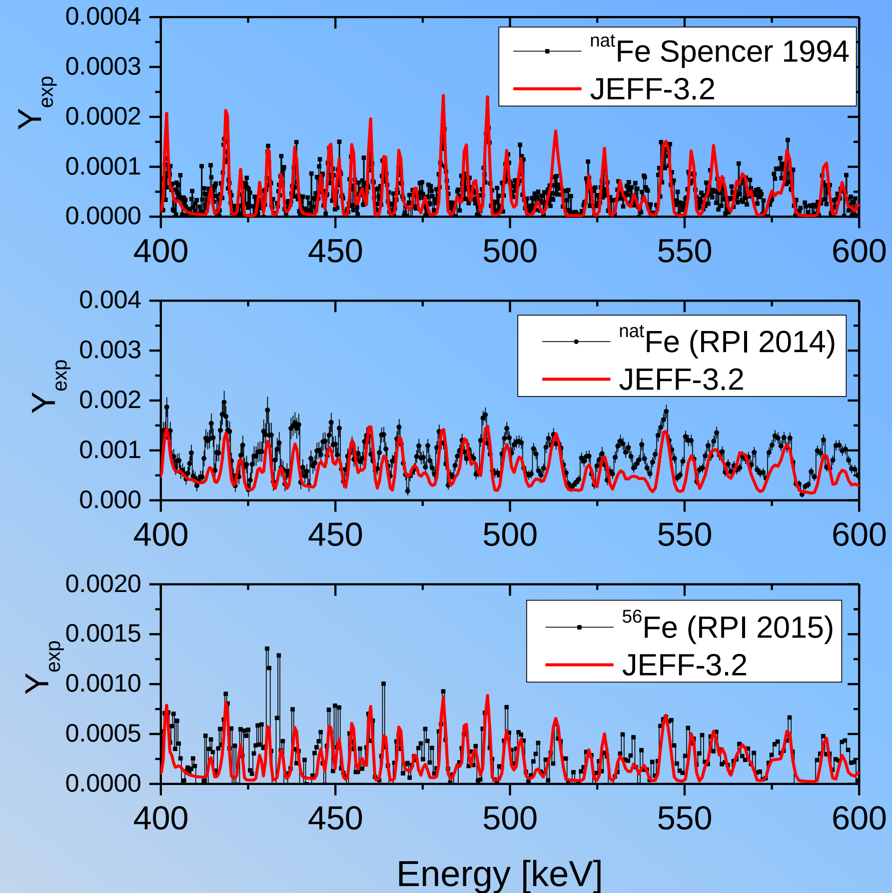
- ENDF/B-VII.1 evaluation for ^{56}Fe has artificial background above 400 keV
- Discrepancies are apparent in MCNP calculations



^{nat}Fe, ^{56}Fe Experimental Results- vs Evaluations using SAMMY

- JEFF 3.2 is matching our experimental data better than ENDF/B-VII.1





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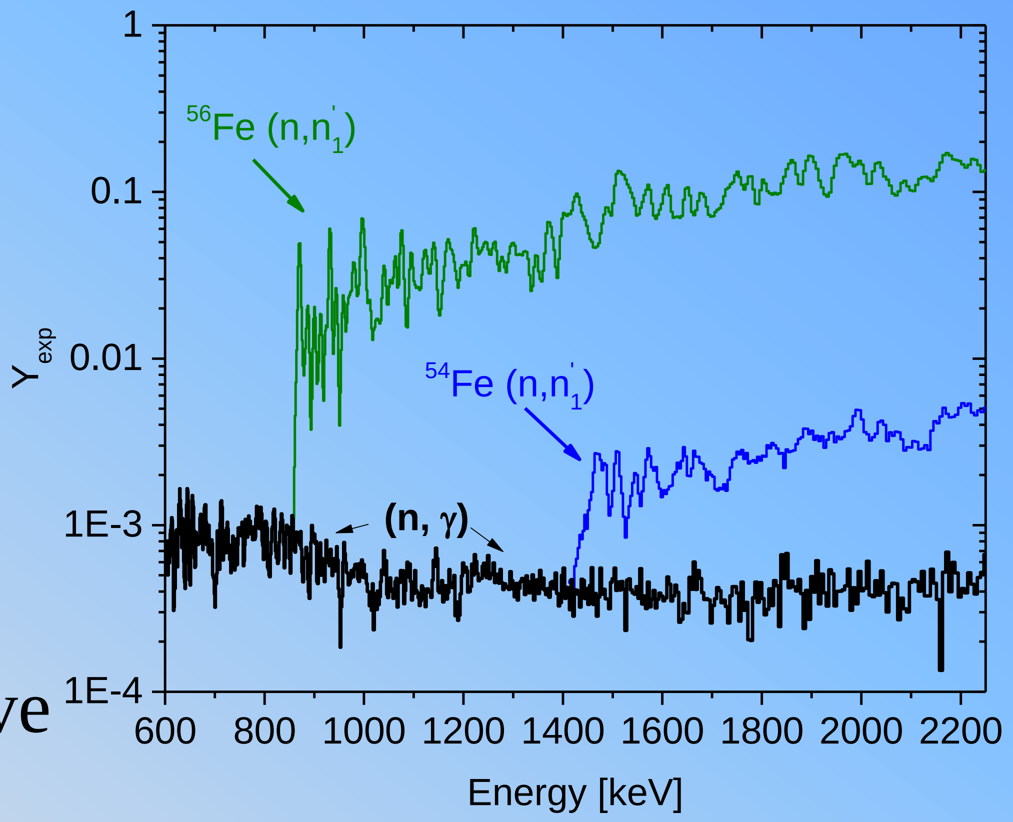
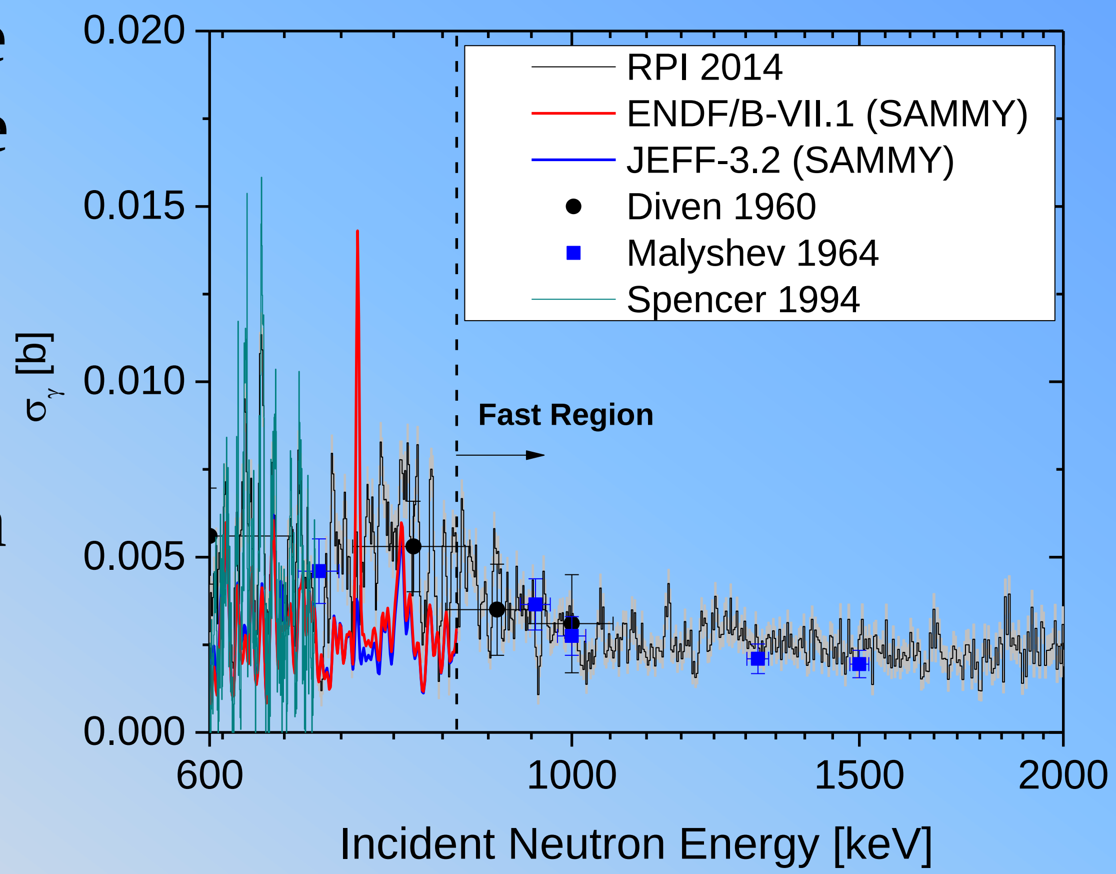
^{nat}Fe Capture for E>850 keV
remove gamma from elastic scattering

- Inelastic states in ^{54}Fe and ^{56}Fe make capture measurements at high energies difficult
- Digital pulse integral discriminator used to remove inelastic scattering signal
- New capture data above 850 keV



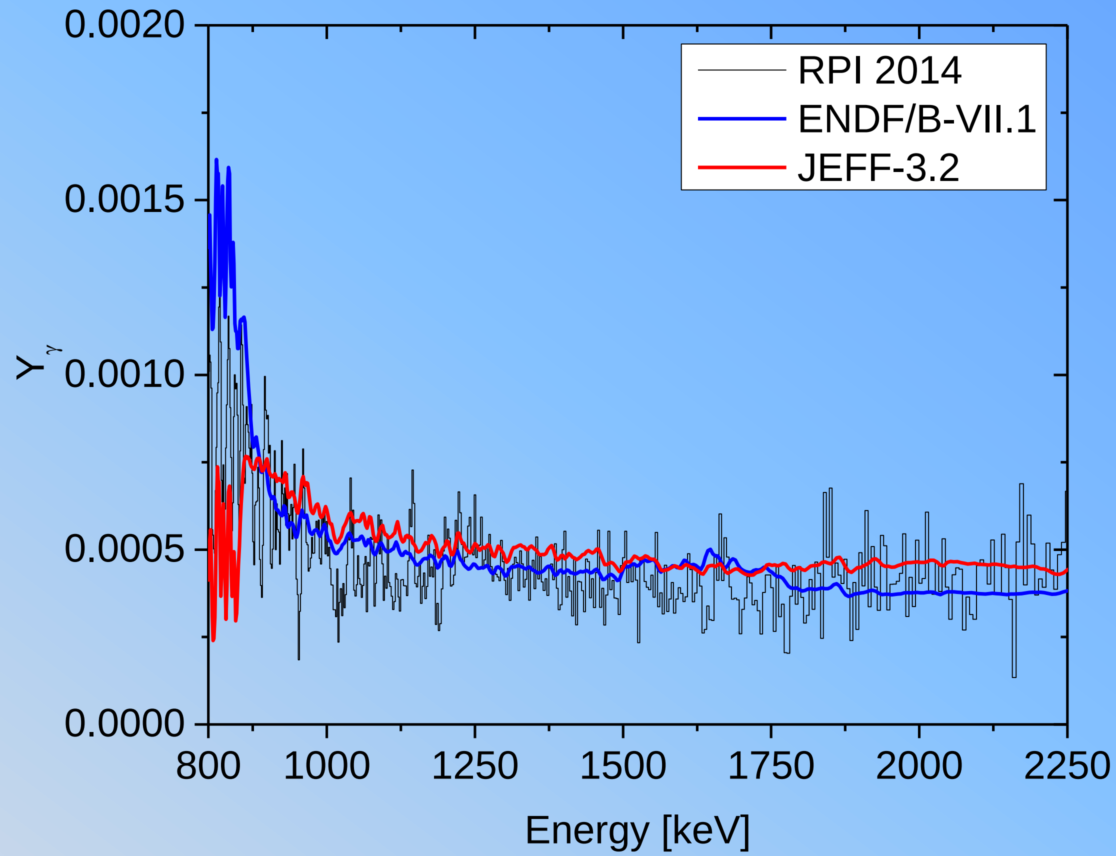
^{nat}Fe Capture above the ^{56}Fe 1st inelastic state

- Fe results incorporate new flux shape above 1 MeV
- Partially resolved structure apparent
- Good agreement with existing experiments



^{nat}Fe Experiment vs evaluations above ^{56}Fe 1st inelastic state

- MCNP calculations of capture yield above 850 keV agree with experimental data
- Noticeable differences between evaluations



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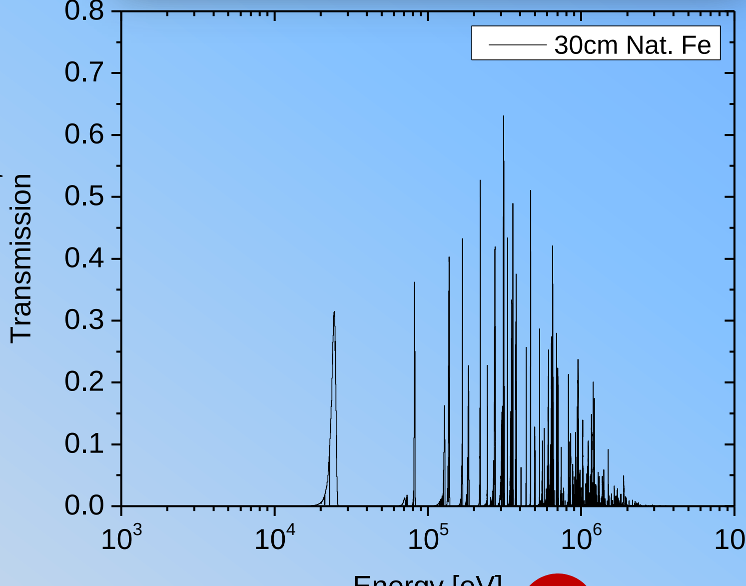
New Method – Fe Filtered Beam Capture Results for ^{181}Ta

- Measurements performed on ^{181}Ta using Fe-filtered beam technique
- 30cm thick Fe filter removes all beam-related gamma and neutron background
- Provides a quasi-monoenergetic neutron source corresponding to deep minima in the Fe cross section



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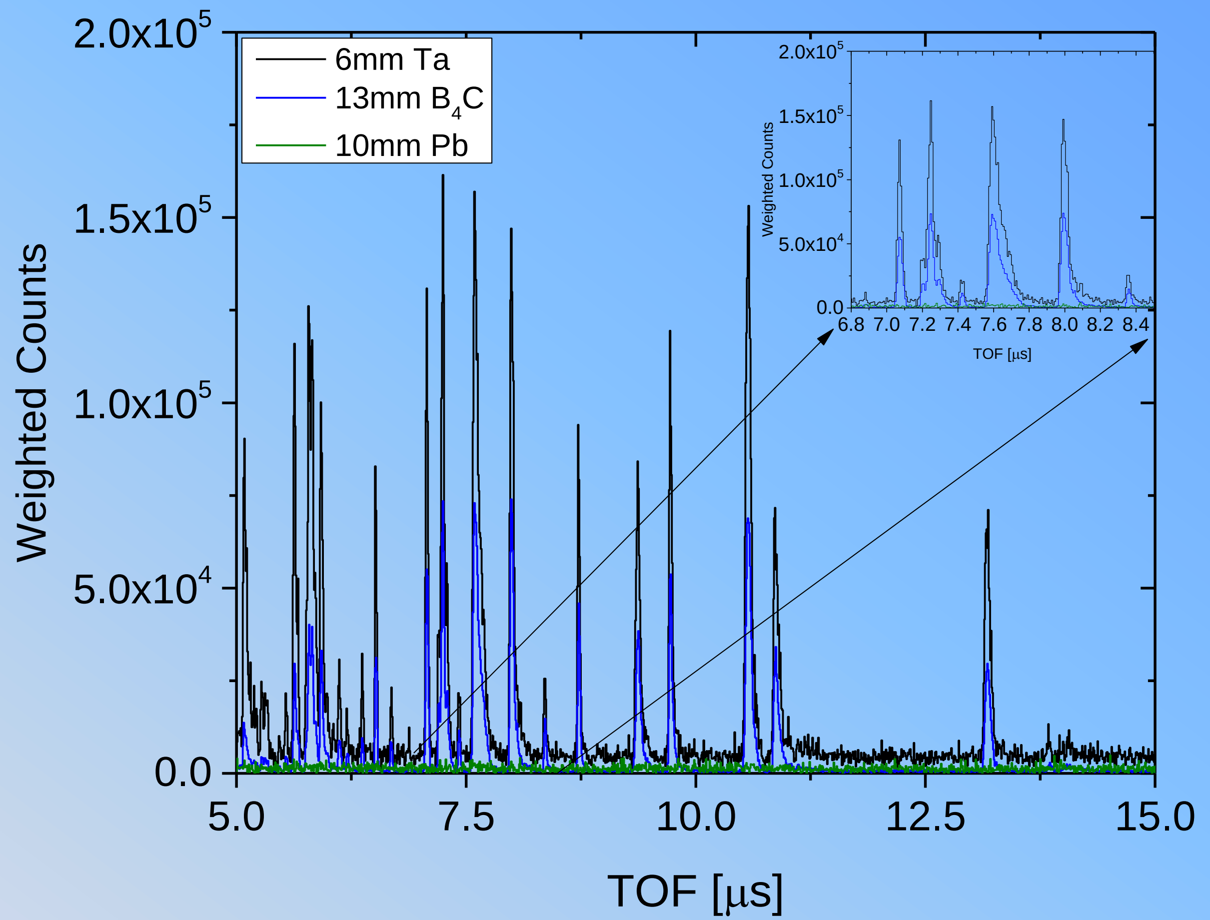
Mid-Energy Capture Detector Experimental Results-^{181}Ta

- Count rates for Ta and B_4C samples were summed under each filter transmission peak.
- Pb scattering sample used to confirm negligible neutron background



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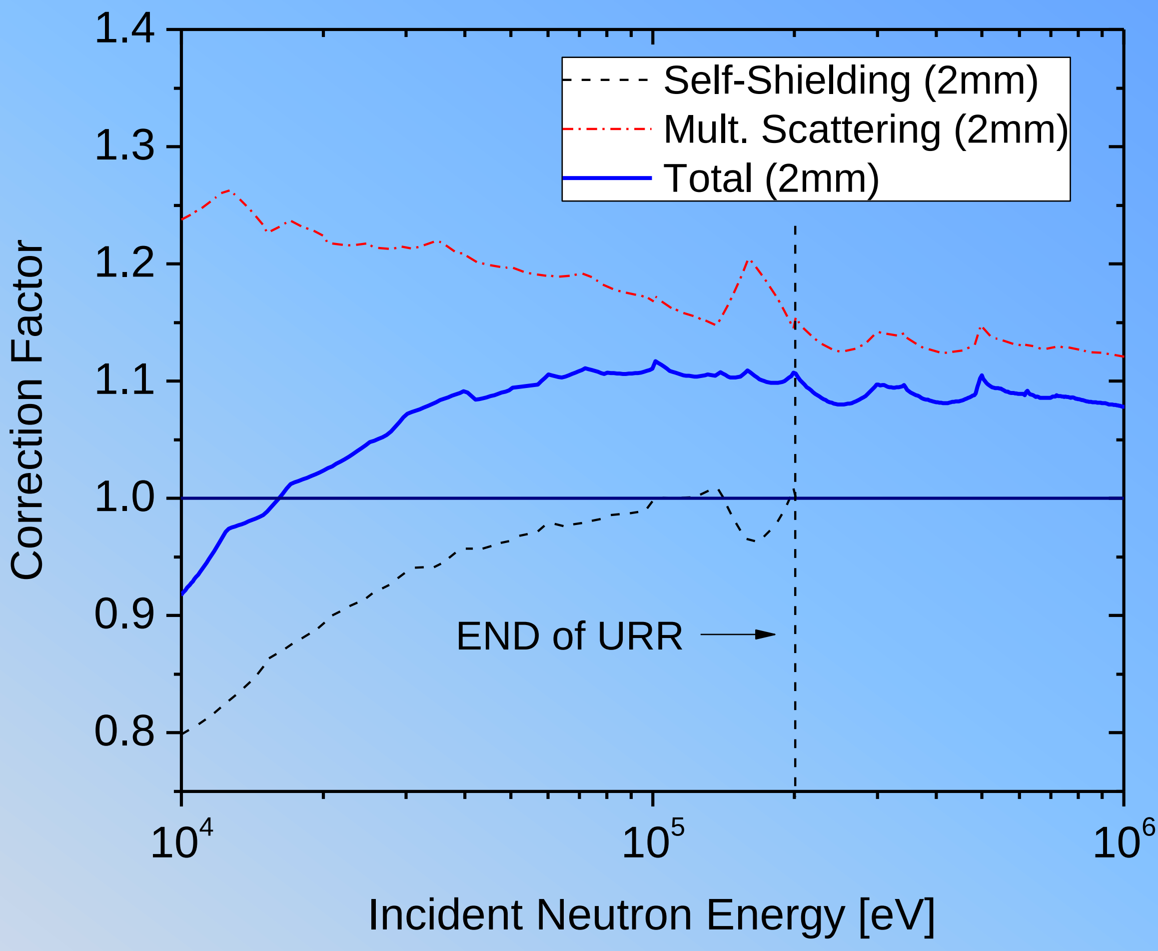
Corrections to the URR Measured Capture Yield

- In the URR corrections for two effects are needed:
  - Multiple scattering (results in observed higher yield)
  - Self shielding (results in observed lower yield)
- The experimental yield is corrected to obtained the cross section.

$$\sigma_\gamma = \frac{Y_{exp}}{N \cdot C} n$$

- Where *N* is the number density, *C* the correction factor and *n* normalization
- The correction works better for thin samples that minimize the self-shielding and multiple scattering



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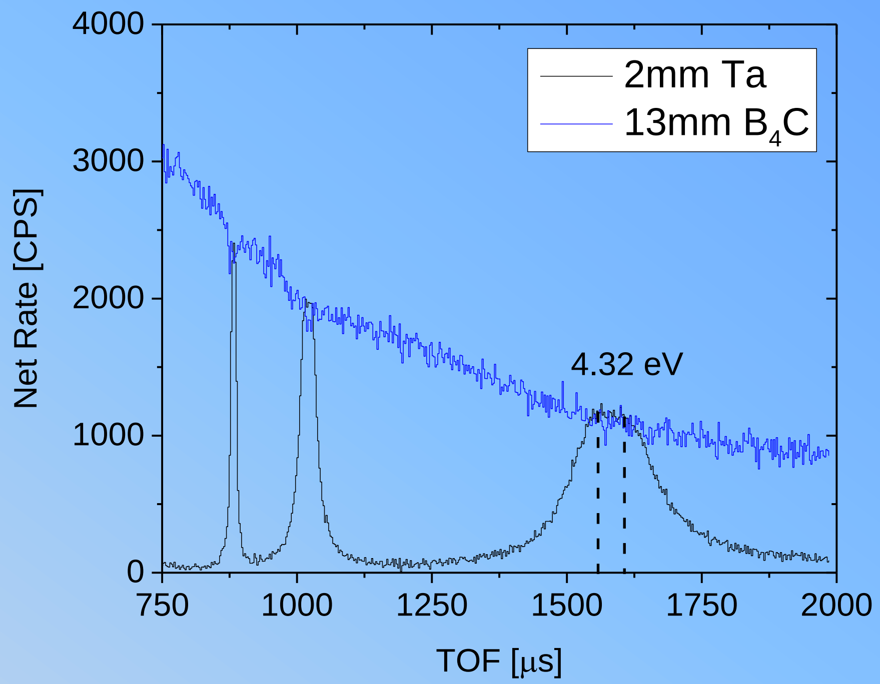
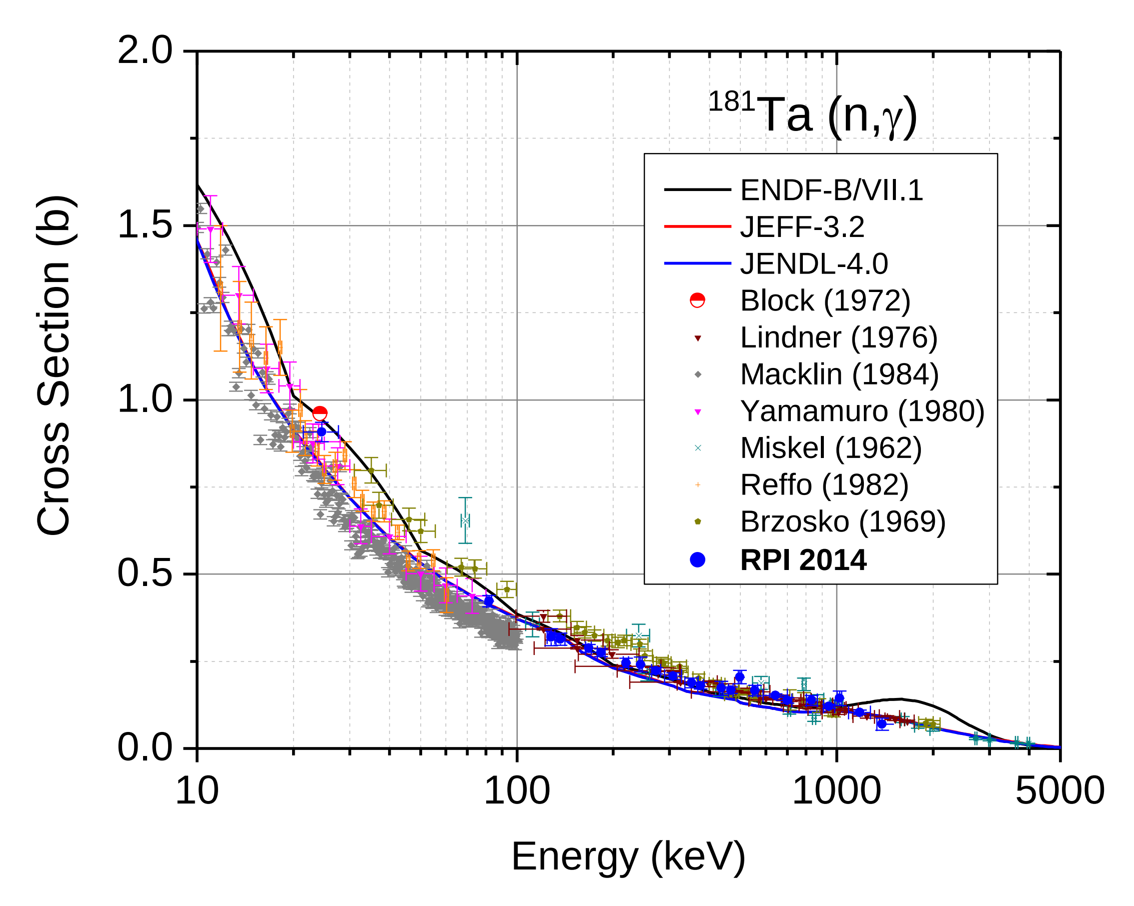
Mid-Energy Capture Detector Experimental Results-^{181}Ta Normalization

- Unfiltered run performed to determine normalization factor from 4.2 eV saturated resonance
- Normalization factor determined from the ratio of B_4C to Ta counts at the location of the saturated resonance ($Y_\gamma \approx 1$)
- A refinement of the normalization is based on a SAMMY calculations



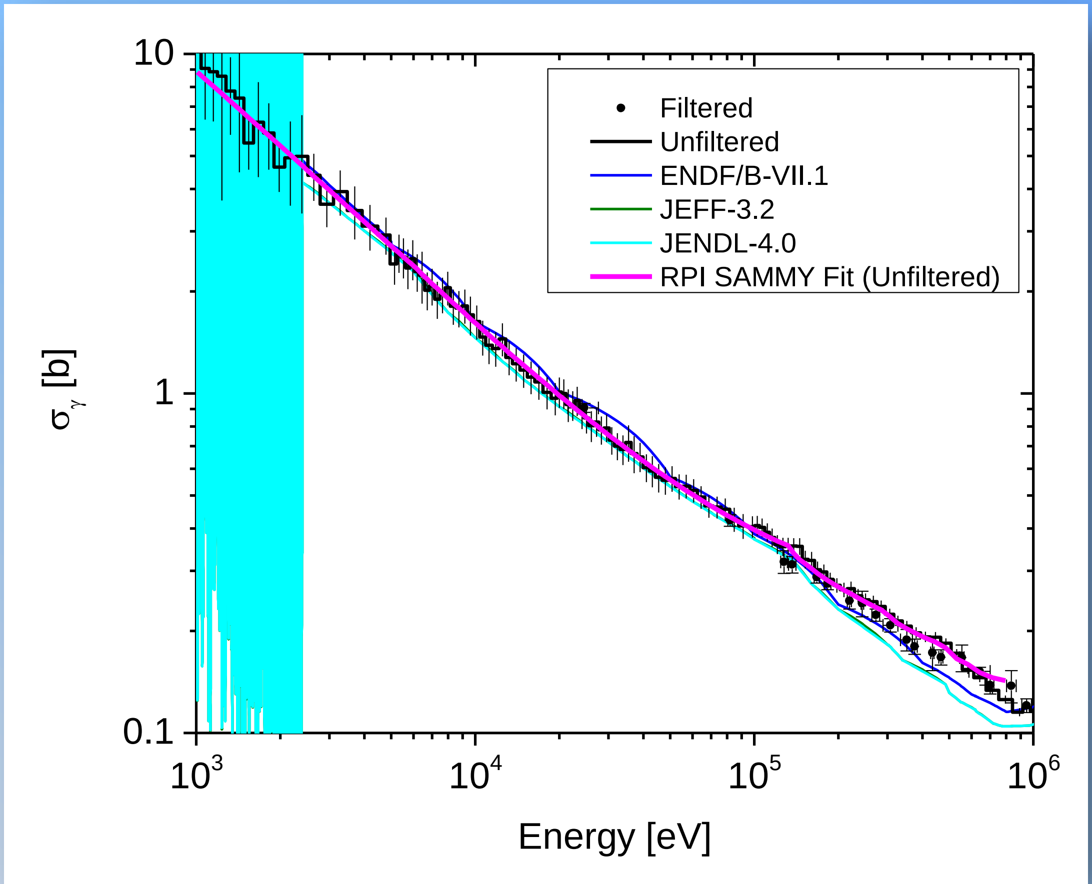
Experimental Fe Filtered Beam Results: ^{181}Ta

- JEFF-3.2 evaluation follows the data better
- ENDB/B-VII have a strange interpolation scheme
- Possible contamination from inelastic scattering apparent in ENDF/B-VII.1



Mid-Energy Capture Detector Experimental Results-^{181}Ta

- Unresolved ^{181}Ta data from 1 keV to 1 MeV
- Good agreement with evaluations
- Self-shielding and multiple scattering corrections performed with SESH
- Average resonance parameters calculated with SAMMY-FITACS



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^{181}Ta - Average Resonance Parameters

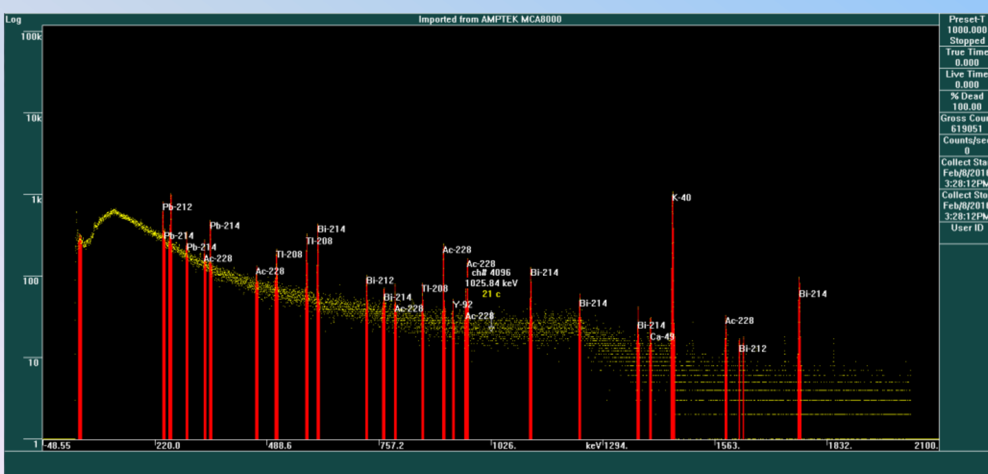
Parameter	RPI Filtered	RPI Unfiltered	Mughabghab 2006	JEFF-3.2
$S_0 \times 10^{-4}$	1.66 ± 0.061	1.64 ± 0.059	1.74 ± 0.12	1.7
$S_1 \times 10^{-4}$	0.545 ± 0.052	0.534 ± 0.050	0.5 ± 0.2	0.2
$S_2 \times 10^{-4}$	2.3 ± 0.2	2.4 ± 0.23	2.3 ± 0.3	2.3
$< \Gamma_{\gamma 0} >$ [eV]	0.065 ± 0.0025	0.063 ± 0.0021	0.0605 ± 0.0020	0.065

- Calculated from 10-800 keV using SAMMY-FITACS
- Use JEFF 3.2 total cross section
- Agreement with published values
- ENDF does not have quoted values for URR parameters

Ce Sample Rental

- New lease program: activation limit 0.6 Bq/g
  - Purchase 30 mg to be analyzed at ORNL as baseline activity
  - Purchase 30 mg to be analyzed after the experiment
  - If activity increased by more than 0.6 Bq/g then renter must purchase the sample ($$$$)

- Used 30 mg of Ce and irradiated in high flux short time conditions equivalent to experimental conditions of cross section measurement.
- HPGE spectroscopy did not detect activity 3 days after irradiation
- Sample was sent back to ORNL for analysis

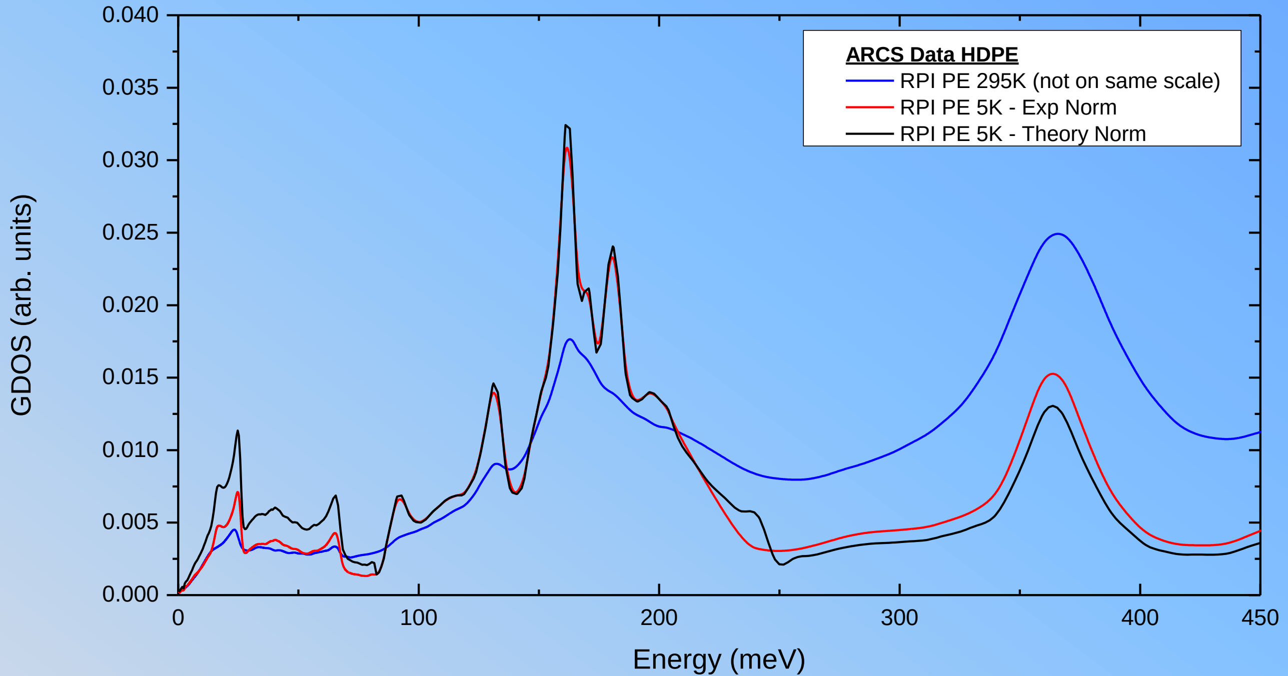


ND 2 - Thermal Scattering

Thermal Scattering Overview

- Preformed measurements at SNS
  - SEQUOIA
    - Water
    - Medium Density Polyethylene (MDPE)
  - ARCS
    - High Density Polyethylene (HDPE) 295 °K and 5 °K
    - Quartz (SiO_2) at 20, 300 550, 600 °C
  - VISION (measures S(ω))
    - Lucite, Lexan, Polyethylene at 5 °K and 295 °K
- The double differential scattering data (DDSD) can be used to benchmark thermal scattering evaluations
- Methods to generate S(α,β) from the experimental data are under development:
  1. Convert the data (S(Q,ω)) to phonon spectrum (use low values of Q to limit multiple phonon scattering)
  2. Remove the elastic peak from the DDSD and convert the inelastic part directly to S(α,β)
- Developed capabilities to use LAMMPS code to calculate the phonon spectrum and scattering kernel.

Phonon spectrum from measured *S*(*Q*,*E*)



- Low temperature measurements are essential in order to resolve the structure.
- Convert the measured $S(Q,E)$ data for phonon spectrum using the SNS DAVE code:

$$S(Q,E)=\frac{\hbar^2 Q^2}{6ME}\exp(-\langle u^2\rangle Q^2)G(E)[n(E,T)+1] \qquad n(E,T)=\frac{1}{\exp\left(\frac{E}{k_B T}\right)-1}$$

$G(E)$ - generalized phonon density-of-states(GDOS),

Q - wave vector transfer,

$S(Q,E)$ - structure dynamics factor,

M - mass of the atom,

$\langle u^2\rangle$ - mean square displacement.

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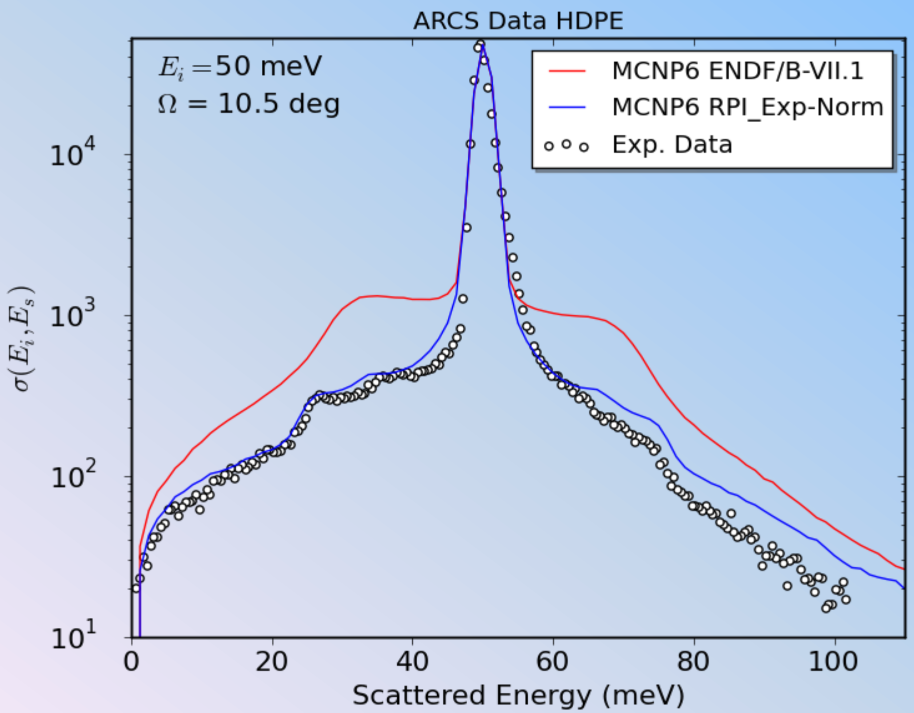
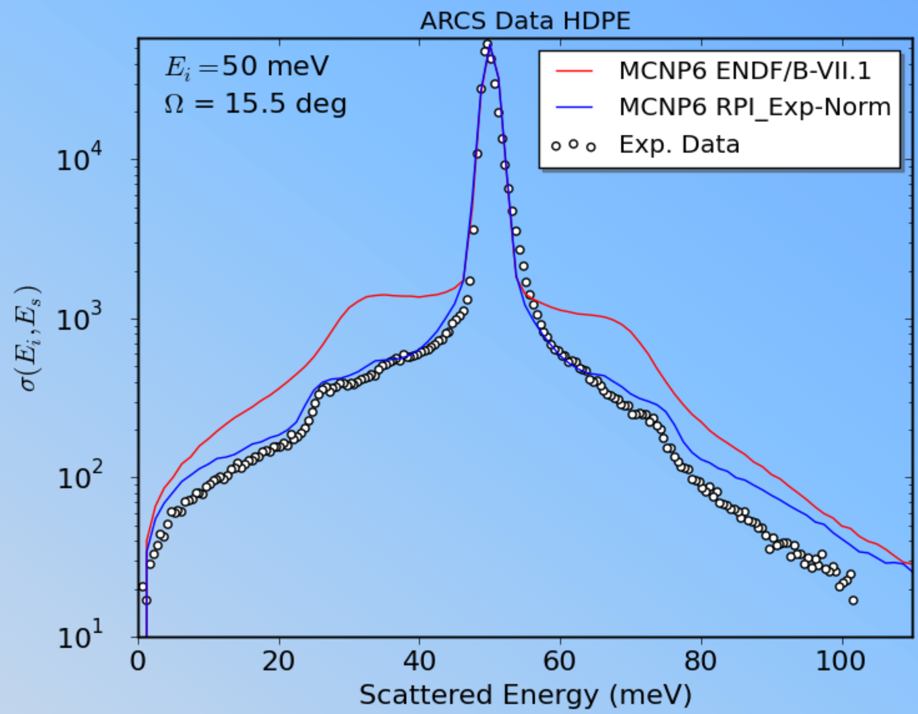
Example for HDPE

Experiment Normalized GDOS

- The phonon spectrum was processed with NJOY 2012
- The experimental response simulated with MCNP 6
- The agreement with the experiment is improved





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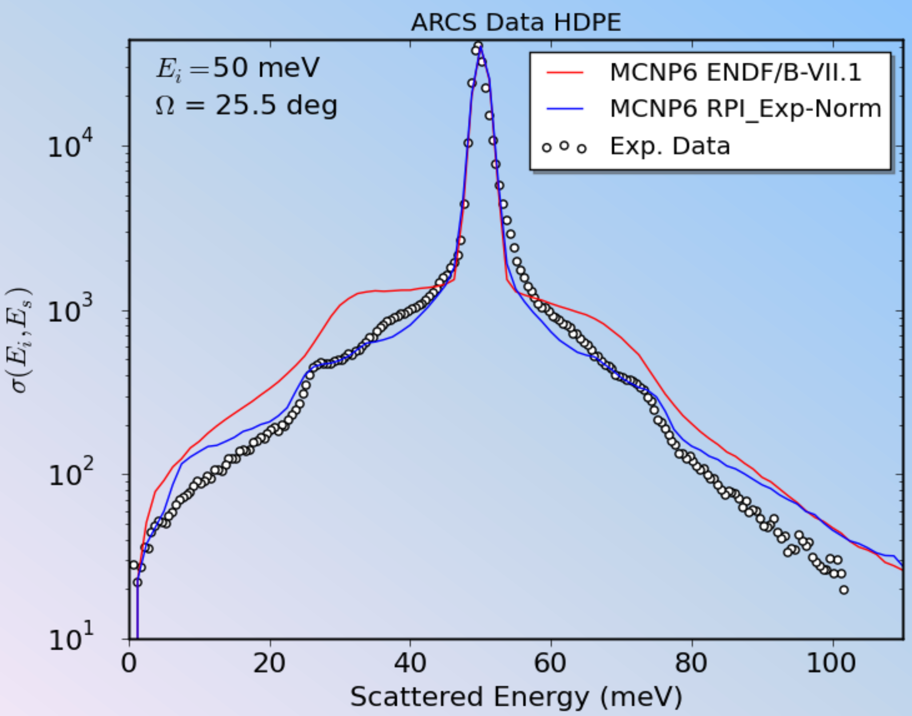
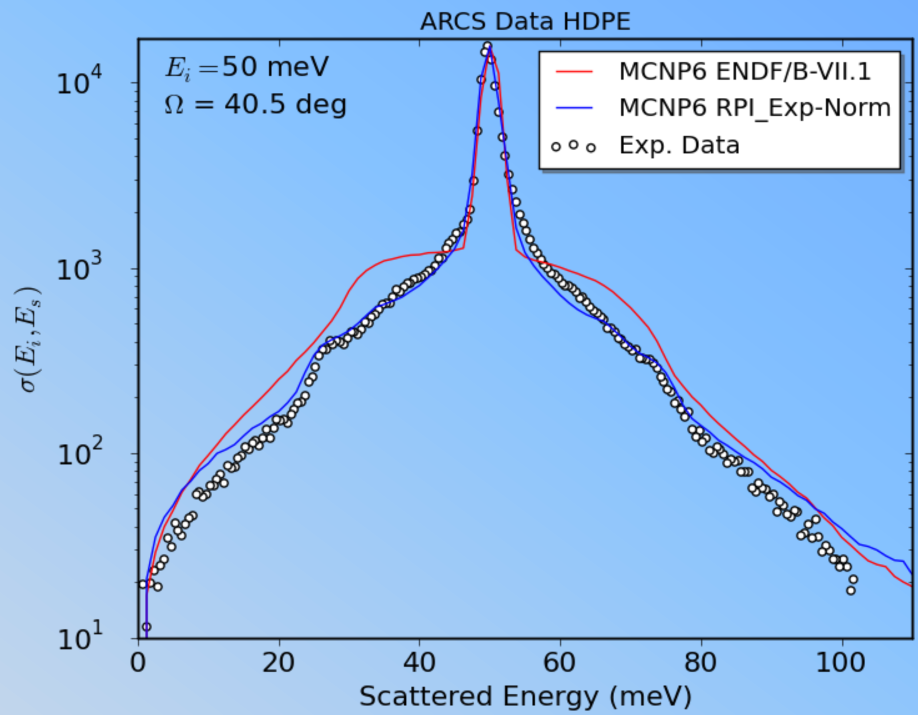
Example for HDPE other angles Experiment Normalized GDOS

- Similar improvements
- Other incident energies and angles available





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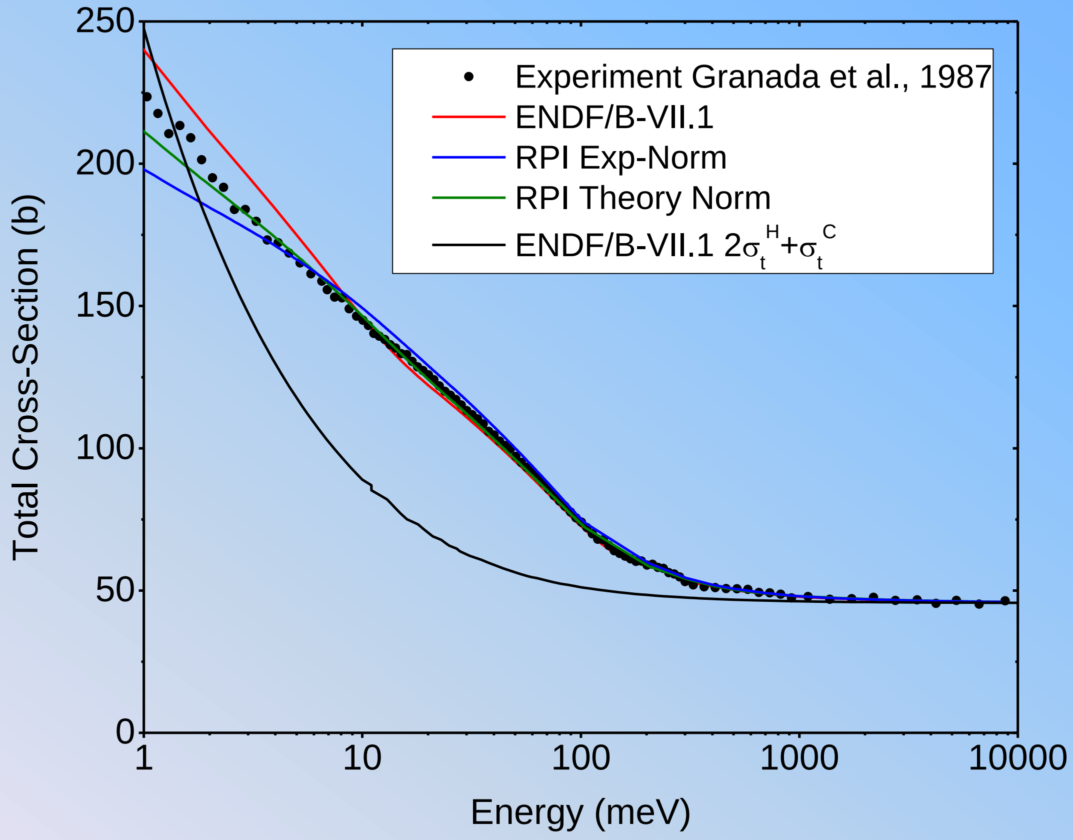
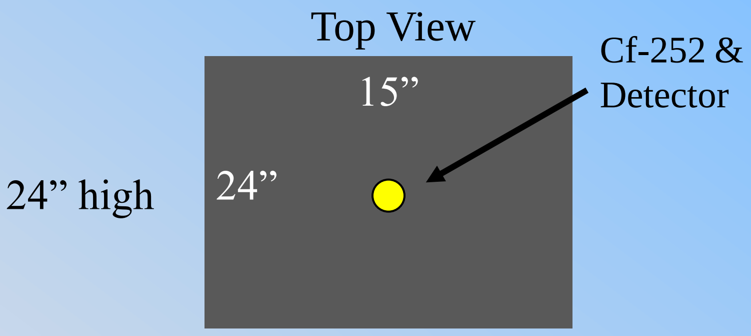
Polyethylene Total Cross Section

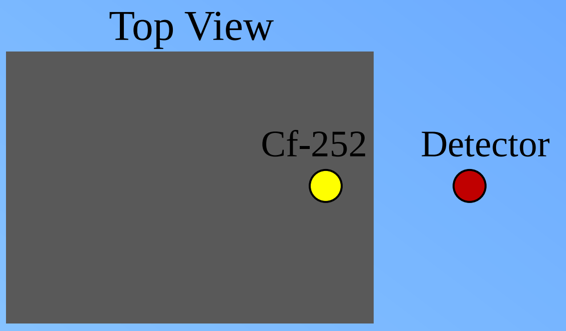
- The experimentally derived phonon spectrum is in good agreement with the total cross section measurement.
- Experimental vs theoretical normalization give slightly different results

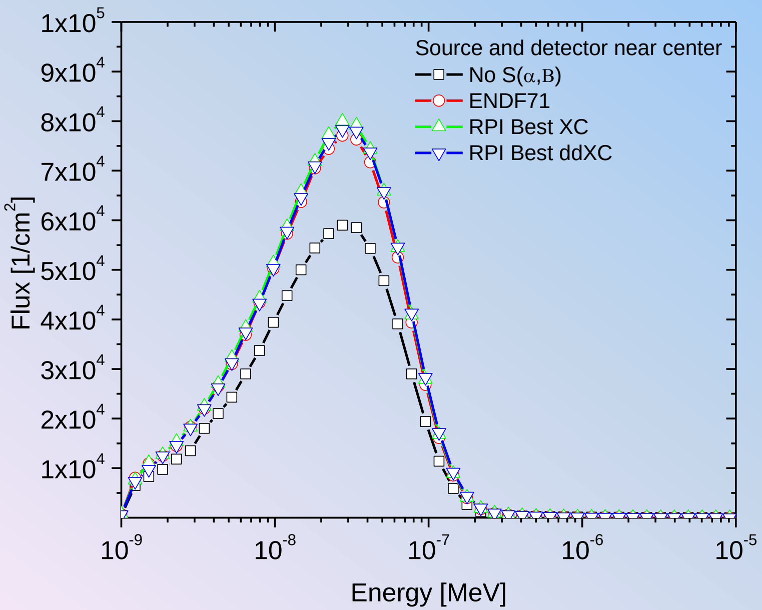


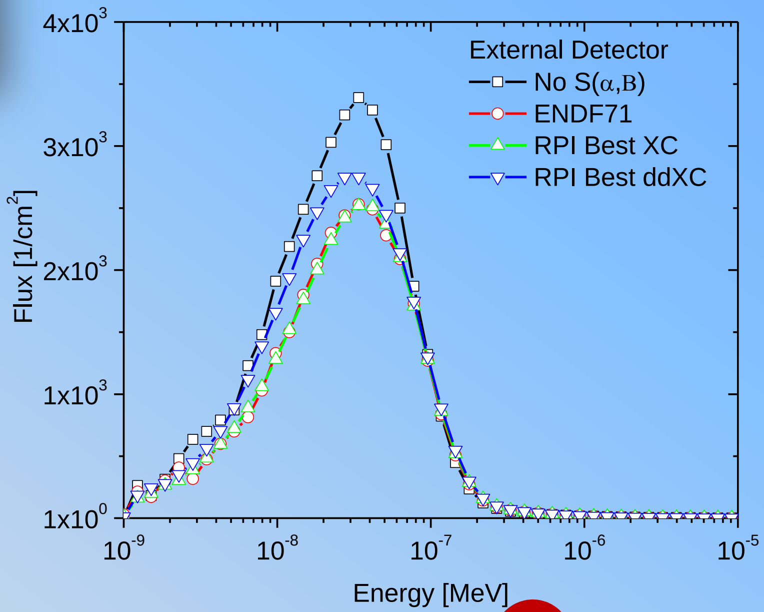
Benchmarking for Polyethylene

- Simulate a geometry with a Cf-252 point source in a large polyethylene moderator
  - Seems that the external detector case is sensitive to small variations in the scattering kernel



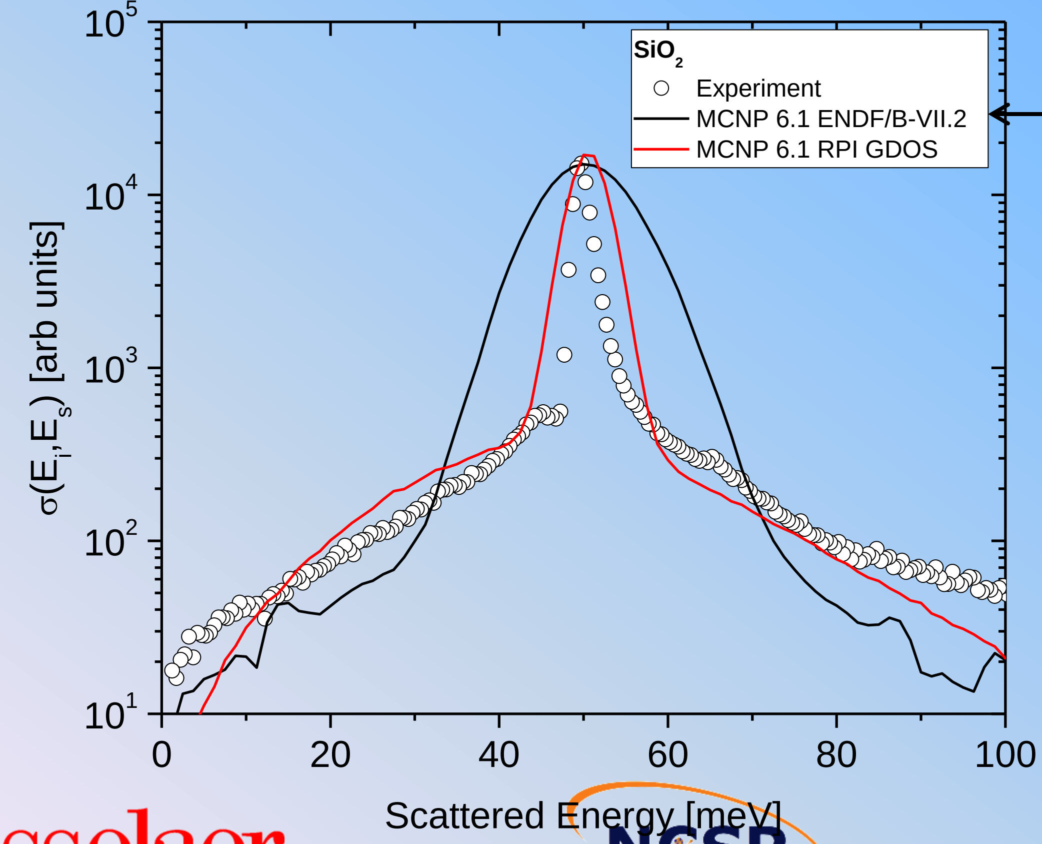






ARCS Quartz Crystal

- SiO_2 was measured at multiple thicknesses
  - 0.3175 cm and 0.635 cm (1/8th and 1/4th inches)
  - Temperatures: 20º C, 300º C, 550º C, 600º C
- Experiment and simulation based on ENDF/B-VII.1 are not in good agreement
  - Are we measuring the same material that was evaluated?
- Preliminary experimental GDOS looks promising.



Indicates the updated quartz evaluation

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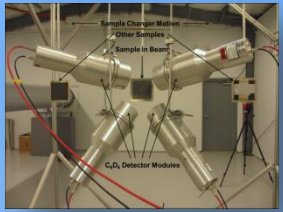
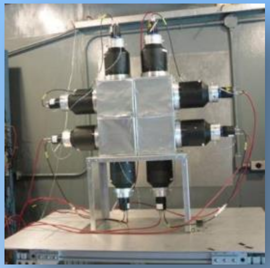
ND 3 - LINAC 2020 Refurbishment and Upgrade Plan

LINAC 2020 – Capabilities Improvement

- Improvement in short pulse operation:
  - **Currently**: pulse width: 6 ns, power: 500 W
  - **Future**: pulse width: 5 ns, power: 5 kW (specs 7 kW)



- Improvement to current setups:
  - **keV Capture**
    - Improve S/N ratio and thus improve accuracy of measured capture yield
    - Enable measurements on smaller enriched (expensive) isotopes samples
    - Reduce multiple scattering and self-shielding by using smaller samples
    - Study gamma coincidence and angular distribution for resonance spin assignment
  - **keV Transmission**
    - Improve S/N ratio by better filtering of the gammas in the beam
    - Enable measurements on smaller enriched (expensive) isotopes samples

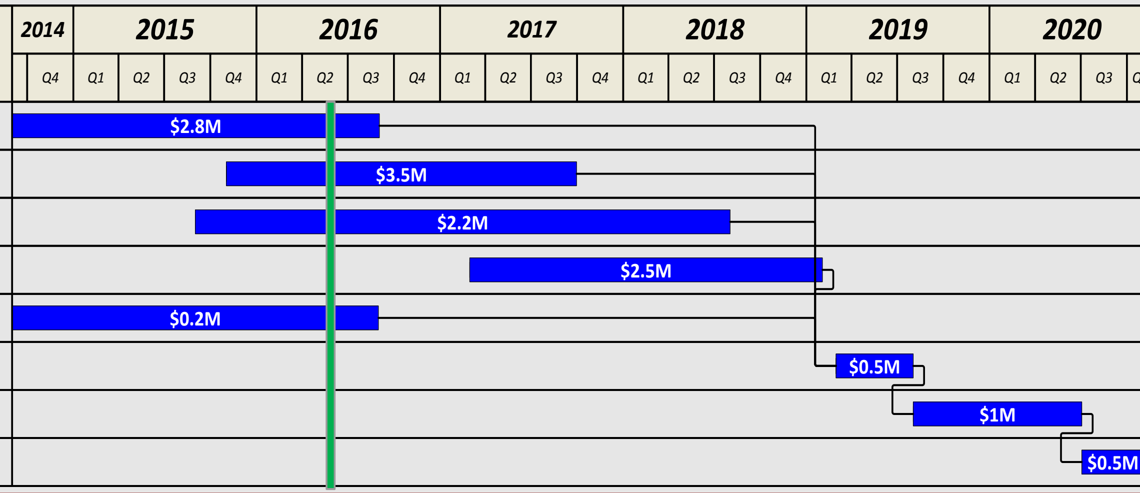


LINAC 2020 - New Capabilities

- Higher neutron flux enables additional capabilities:
  - Measurement on radioactive samples
- New setups:
  - **keV neutron scattering and angular distributions**
    - Help improve evaluations by providing additional data
    - Especially important in the URR
    - Improve energy resolution by moving the system to a longer flight path (45m)
  - **High resolution neutron scattering at 250m.**
    - Improves resonance parameters in the keV region (complements transmission and capture)
  - **Fission cross section measurements**
    - Typically require smaller radioactive samples
  - **Capture on fissile isotopes**
    - Might require coincidence with a fission chamber
  - **Self indication measurements**
    - Can be used to obtain self shielding factors and also test current evaluations.
    - Can provide additional information on resonance parameters and spins.

LINAC 2020 Schedule

ID	Task Name	Start	Finish
1	Klystron Purchase	9/1/2014	9/1/2016
2	Modulator Purchase	11/2/2015	9/29/2017
3	SLAC design work	9/1/2015	8/1/2018
4	Purchase of LINAC sections	3/1/2017	2/1/2019
5	Electron Gun Modification	9/1/2014	8/30/2016
6	Demolition of current LINAC	3/1/2019	8/1/2019
7	Installation of new LINAC	8/2/2019	7/2/2020
8	Acceptance Testing of New LINAC	7/3/2020	11/3/2020



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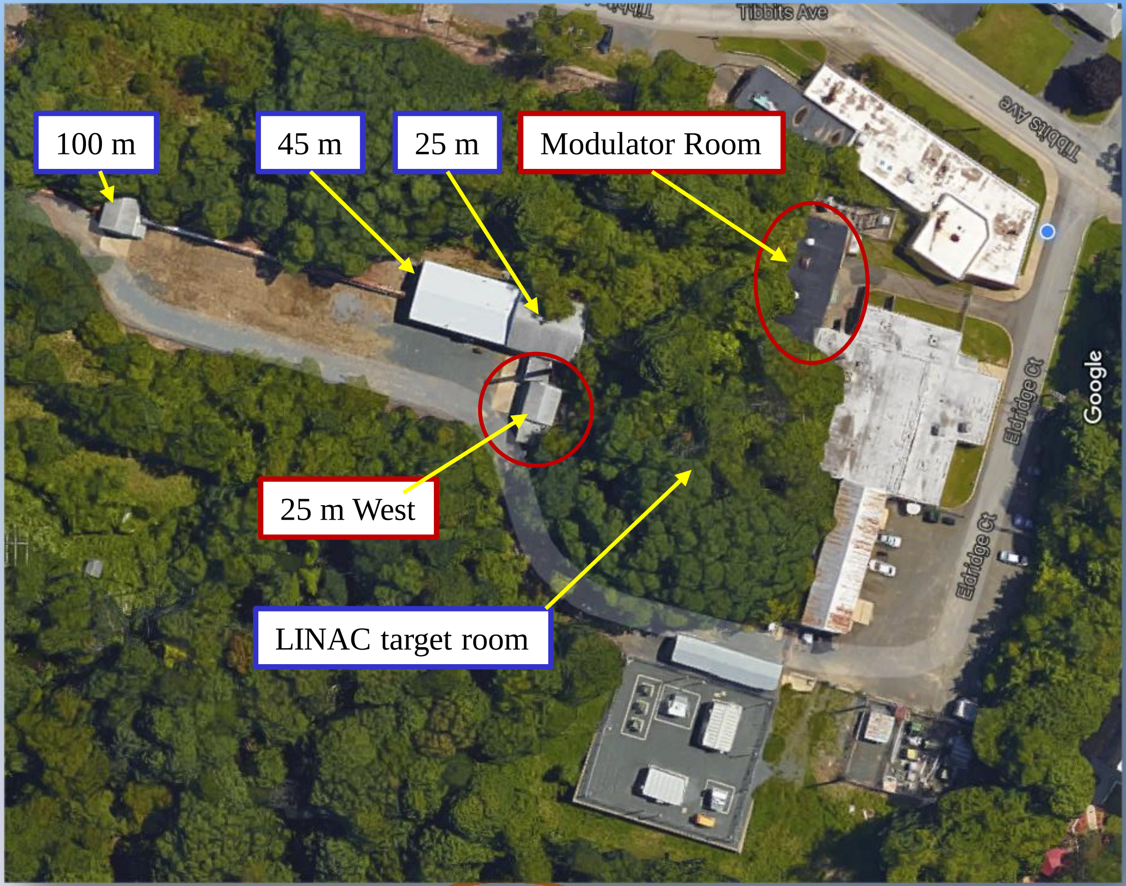
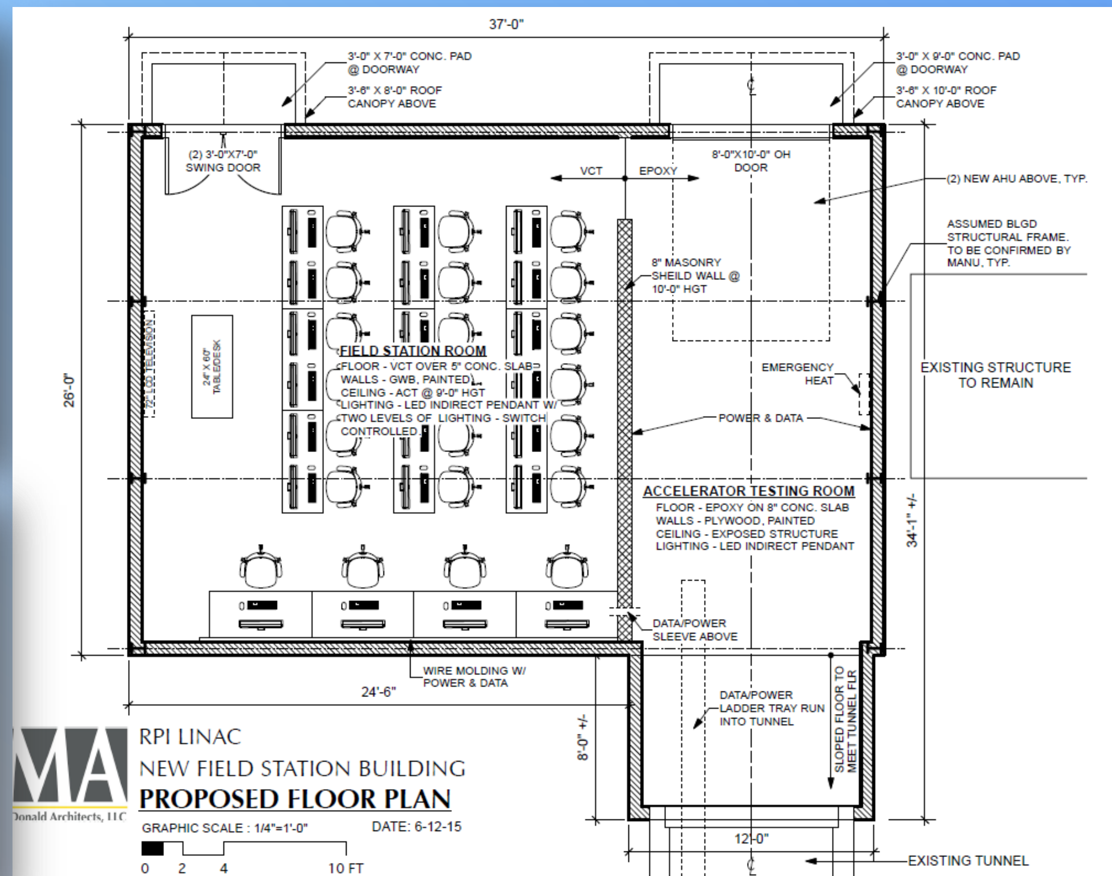
Infrastructure upgrades

- Construct a new teaching/research laboratory
- Increase the size of the modulator room



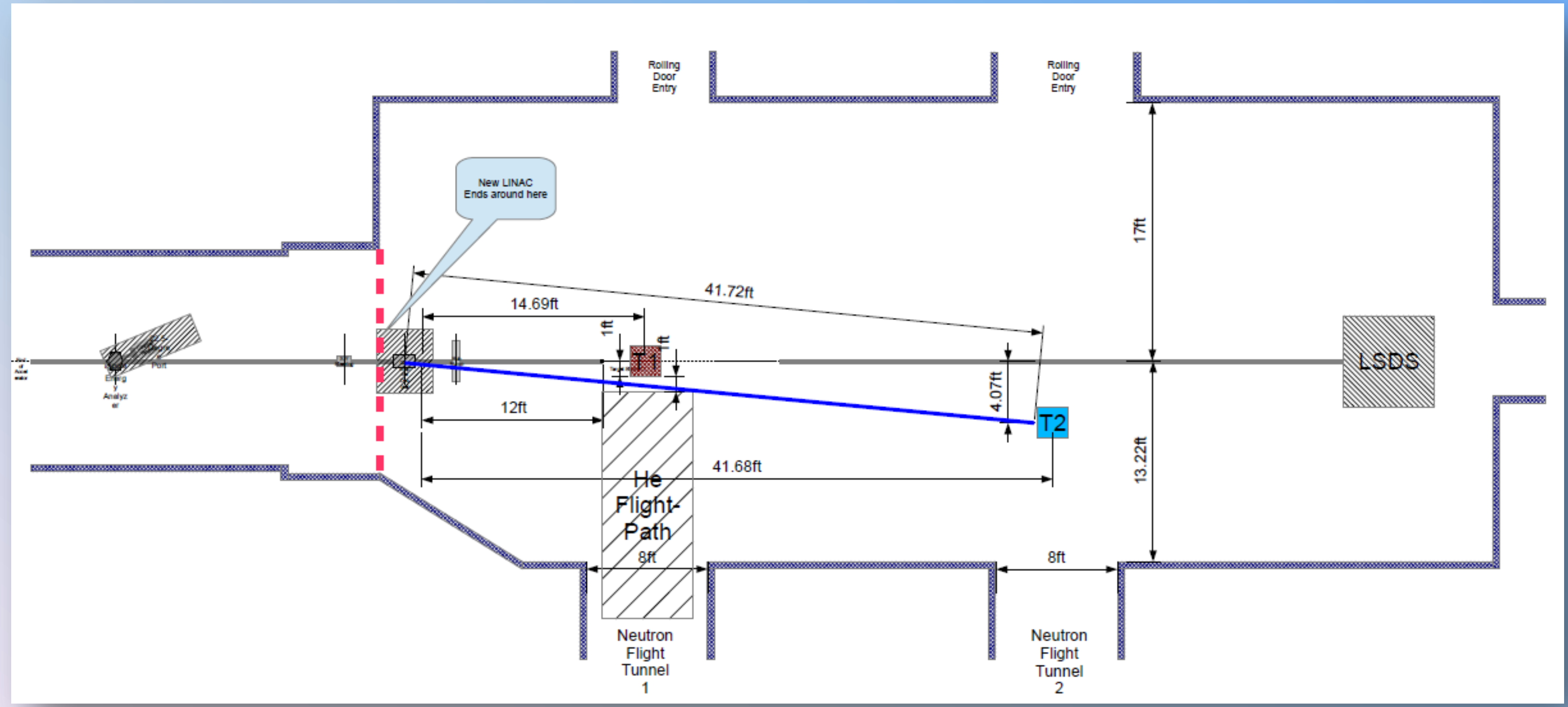
New Research/Education Laboratory

- Create a new laboratory for education and research
  - Construction is funded and executed by RPI VP Administration office



Changes to the target room – new beamline

- Adding a new electron beamline and neutron production target
- RPI is developing remote electron beam deflection to minimize dose to LINAC staff



Beam Magnets

- Purchased magnets, power supplies and misc. vacuum parts from MIT Bates lab surpluses.
- The equipment is now at RPI

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LINAC 2020 Refurbishment and Upgrade Plan

- SLAC
  - Delivered
    - Design concept for the layout of the accelerator.
    - Initial modulators design parameters
  - Working on:
    - Modeling of Gun Electrode System
    - Buncher Electrical Design
    - Solid Model of beamline
- An order for 5 Thales klystrons was sent to the vendor.
  - 1st klystron passed factory acceptance tests with RPI representative
  - Acceptance test for two additional klystrons is scheduled for April
- Planned for FY16
  - Modulators order
  - Accelerator sections design (with SLAC).

Recent related publications

- Y.-R. Kang, M. W. Lee, G. N. Kim, T.-I. Ro, Y. Danon, D. Williams, G. Leinweber, R. C. Block, D. P. Barry, M. J. Rapp, “Neutron Capture Measurements and Resonance Parameters of Gadolinium”, Nuclear Science and Engineering, Volume 180, Number 1, May 2015.
- A. M. Daskalakis, E. J. Blain, B. J. McDermott, R. M. Bahran, Y. Danon, D. P. Barry, G. Leinweber, M. J. Rapp, R. C. Block, “Separation of Neutron Inelastic and Elastic Scattering Contribution from Natural Iron using Detector Response Functions”, 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015
- Brian Mcdermott, E. Blain, A. Daskalakis, N. Thompson, A. Youmans, H.J. Choun, W. Steinberger, Y. Danon, R.C. Block, D.P. Barry, B. Epping, G. Leinweber, M.J. Rapp, “New (n, gamma) measurements on elemental iron from 850 to 2500 keV”, 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015.
- C. Wendorff, K. Ramic, E. Liu, Y. Danon, “Experimental S(α,β) Data for Moderators with Analysis of Current Evaluations”, 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015.
- K. Ramic, C. Wendorf, Y. Danon, and L. Liu, “Improvements to thermal scattering law using new and existing methods”, 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015
- Brian McDermott, E. Blain, A. Daskalakis, N. Thompson, A. Youmans, H.J. Choun, W. Steinberger, Y. Danon, “Capture Cross Sections in nat-Fe and 181-Ta from 1 to 2000 keV using a new C6D6 Detector Array”, International Conference on Nuclear Criticality Safety, Charlotte, NC, September 2015